Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra

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Received 13 January 2011; revised 5 July 2011; accepted 26 July 2011; published 25 October 2011.

[1] With global warming, snowmelt is occurring earlier and growing seasons are becoming longer around the Arctic. It has been suggested that this would lead to more uptake of carbon due to a lengthening of the period in which plants photosynthesize. To investigate this suggestion, 8 consecutive years of eddy covariance measurements at a northeastern Siberian graminoid tundra site were investigated for patterns in net ecosystem exchange, gross primary production (GPP) and ecosystem respiration (R_{eco}). While GPP showed no clear increase with longer growing seasons, it was significantly increased in warmer summers. Due to these warmer temperatures however, the increase in uptake was mostly offset by an increase in R_{eco}. Therefore, overall variability in net carbon uptake was low, and no relationship with growing season length was found. Furthermore, the highest net uptake of carbon occurred with the shortest and the coldest growing season. Low uptake of carbon mostly occurred with longer or warmer growing seasons. We thus conclude that the net carbon uptake of this ecosystem is more likely to decrease rather than to increase under a warmer climate. These results contradict previous research that has showed more net carbon uptake with longer growing seasons. We hypothesize that this difference is due to site-specific differences, such as climate type and soil, and that changes in the carbon cycle with longer growing seasons will not be uniform around the Arctic.

Citation: Parmentier, F. J. W., M. K. van der Molen, J. van Huissteden, S. A. Karsanaev, A. V. Kononov, D. A. Suzdalov, T. C. Maximov, and A. J. Dolman (2011), Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra, *J. Geophys. Res.*, *116*, G04013, doi:10.1029/2011JG001653.

1. Introduction

[2] The stability of the net carbon exchange of tundra under a changing climate depends on the combined response of ecosystem respiration (R_{eco}) and gross primary production (GPP). A longer growing season, caused by earlier snowmelt, may increase GPP. It has been suggested that this would result in an increase in biomass and carbon sink [*Churkina et al.*, 2005]. However, R_{eco} may also increase due to the longer snow-free periods, stimulated by overall higher temperatures, and in turn this would reduce the magnitude of the carbon sink. Since the Arctic contains large amounts of carbon in its cold, frozen soils [*Tarnocai et al.*, 2009], the specific way in which GPP and R_{eco} in Arctic ecosystems react can have large impacts on the global carbon cycle [*McGuire et al.*, 2009].

[3] Changes in the Arctic are not only expected but some have already been observed. Arctic temperatures are rising faster than the global average [*Serreze et al.*, 2000; *Chapin III et al.*, 2005; *Kaufman et al.*, 2009], and it has been shown that snowmelt in the Arctic is occurring earlier, from several days up to two weeks per decade [*Dye*, 2002; *Smith et al.*, 2004; *Høye et al.*, 2007]. While these changes in snowmelt seem small in absolute terms, they are large relative to the short Arctic growing season. This has already led to an earlier flowering of plants and a higher primary productivity [*Myneni et al.*, 1997; *Zhou et al.*, 2001; *Høye et al.*, 2007; *Post et al.*, 2009]. In contrast to this increase in the uptake of carbon, respiration is also likely to increase with higher temperatures [*Lloyd and Taylor*, 1994]. Recently it has been shown that increases in respiration can also originate from deeper soil layers that have become available for respiration after permafrost degradation [*Schuur et al.*, 2008; *Dorrepaal et al.*, 2009]. Since GPP and respiration fluxes act in opposite directions, their relative change will determine the future sink function of these ecosystems [*Welker et al.*, 2004].

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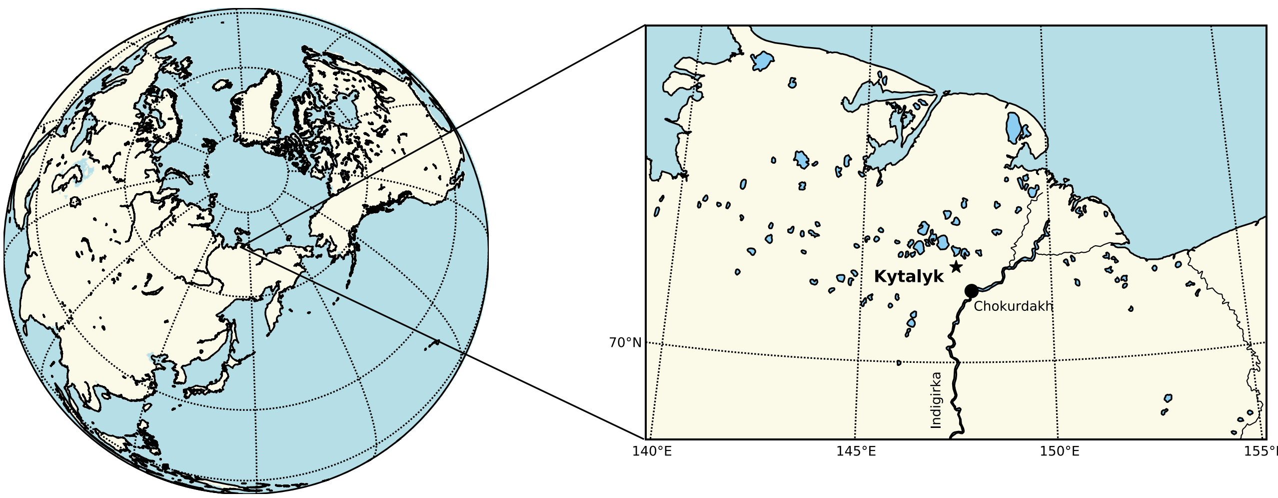

Figure 1. Location of the research site "Kytalyk" within northeastern Siberia, 30 km northwest of the town of Chokurdakh.

[4] Although estimated future changes in GPP and R_{eco} have been simulated in models, at the moment more, especially long term, measurements are required to determine realistic responses [*Piao et al.*, 2007; *Sitch et al.*, 2007; *Euskirchen et al.*, 2009]. In the past, a number of eddy covariance studies of carbon cycling in the Arctic have been established that provide more insight in the dynamics of this ecosystem. However, most of these studies have been performed in Scandinavia or Alaska because of the difficult logistic conditions in the rest of the Arctic [*Fan et al.*, 1992; *Oechel et al.*, 2000; *Williams et al.*, 2000; *Hargreaves et al.*, 2001; *Harazono et al.*, 2003; *Aurela et al.*, 2004; *Beringer et al.*, 2005; *Kwon et al.*, 2006; *Lund et al.*, 2010]. And although the Siberian part of the Arctic has been studied in several eddy covariance studies [*Corradi et al.*, 2005; *Kutzbach et al.*, 2007; *van der Molen et al.*, 2007], stations with long term measurements of 5 years or more, which are required to observe the inter annual variation of carbon fluxes, still remain scarce outside of Alaska and Scandinavia [*Groendahl et al.*, 2007].

[5] This paper presents the first long-term (>5 years) data set from a northeastern Siberian tundra site, spanning the period 2003 to 2010. To our knowledge, there are no other stations in the region that have a measurement record of similar length, and these measurements fill a large gap in our knowledge of the carbon cycling of this region. By breaking down the measurements of net ecosystem exchange to its components, R_{eco} and GPP, we will show how these carbon fluxes change along a large range of summer temperatures and different growing season lengths. This study uses these relationships to show that the net carbon uptake of this ecosystem does not increase with longer growing seasons and that warmer summer temperatures are more likely to reduce the sink strength rather than to increase it.

2. Materials and Methods

2.1. Site Description

2.1.1. Climate

[6] The study site (70°49′44.9″N, 147°29′39.4″E) lies in the nature reserve Kytalyk, 30 km northwest of the town of Chokurdakh in the republic of Yakutia (Sacha) in northeastern Siberia, as indicated in Figure 1. The climate of this region is continental with temperatures as low as −25°C to −40°C in winter, 5°C to 25°C in summer and an annual average of −10.5°C. The large variation in summer temperatures is due to the close proximity of the Arctic Ocean, 100 km to the north. When the wind is coming from this direction, temperatures are low and when the wind is coming from the warm Siberian continent to the south, temperatures are high. During the summer, 50% of the yearly precipitation falls as rain, while the other half falls as snow during the rest of the year. The total yearly precipitation is low with an average of approximately 220 mm.

[7] Snowmelt usually occurs at the end of May or the start of June. While the snow disappears quickly, the vegetation response to snowmelt lags a significant amount of time. Shrubs do not break bud until after approximately 4 weeks, when a significant amount of heat has been accumulated in the soil, leading to the establishment of a thawed layer, and air temperatures have risen high enough. After bud break, GPP rates are highly variable from day to day, but the average flux over longer time periods, such as weeks, shows stable trends throughout the season [this study]. The growing season usually stops again at the end of August or the start of September, when daylight quickly diminishes and temperatures are rapidly dropping.

2.1.2. Soil, Vegetation and Hydrology

[8] The research area is located in a depression that originally formed the lake bed of a thaw lake of probably Early Holocene age, that was drained in the past by fluvial erosion. The topsoil consists of an organic layer of 10 to 15 cm, underlain by silt deposits. Although the area has no significant slope, apart from some isolated hills, cryogenic processes have led to micro topographical differences within the landscape, where ice lenses have created small mounds or palsa-like features which cause elevation differences of at most a meter. In between these higher areas, depressions occur where standing water remains during summer, especially in areas where ice wedges are actively expanding, and in some areas small ponds are created. Ice-wedge polygons

also occur within the area, although they are less clearly visible near the measurement tower.

[9] The vegetation of this site falls within the graminoid tundra class (tussock-sedge, dwarf-shrub, moss tundra) of the circumpolar Arctic vegetation map [*Walker et al.*, 2005]. Vegetation in the drier areas consists of *Betula nana* and *Salix pulchra* shrubs, *Eriophorum vaginatum* sedges and mosses. Toward the wetter areas, shrub cover diminishes and *Sphagnum* mosses, *Caluna palustris* and the sedges *Eriophorum angustifolium* and *Carex aquatilis* are more common, with the latter two dominating the wettest parts. Vegetation height varies from 20 to 30 cm in the shrub dominated areas to 40 to 50 cm in the sedge dominated areas. The water level in the sedge dominated depressions can show considerable differences up to 10 cm within the season and among years, while in the shrub dominated dry areas there is no groundwater level until the permafrost, and changes are less apparent. Although water level is highly heterogeneous in the area, soil moisture changes are less abrupt and most soils remain moist during the growing season.

2.2. Instrumentation

[10] Starting in April 2003, wind speed and temperature were measured with the use of a sonic anemometer (Gill Instruments, Lymington, UK, type R3-50) and concentrations of CO_2 and water vapor were measured with an open path infrared gas analyzer (Licor, Lincoln, Nebraska, USA, type Li-7500), both installed at the top of a small mast at 4.7 m. The data was logged on a hand-held computer [*van der Molen et al.*, 2006] at a rate of 5–10 Hz in the first few years, depending on storage capacity and time between field visits. Since 2007, when storage capacity was upgraded, measurements have been performed consistently at 10 Hz, and it has been shown that these results do not differ significantly from the measurements taken at a lower rate [*van der Molen et al.*, 2007]. Fluxes were calculated according to the Euroflux methodology [*Aubinet et al.*, 2000], with the addition of the angle of attack calibration [*van der Molen et al.*, 2004; *Nakai et al.*, 2006]. Afterward, these measurements were gap-filled according to the standard gap-filling method used by the Fluxnet community [*Reichstein et al.*, 2005; *Moffat et al.*, 2007].

[11] In the use of an open path infrared gas analyzer (IRGA), as in this research, it has been suggested to correct for the surface heat exchange from the instrument itself when measuring under cold temperatures or snow-covered conditions [*Burba et al.*, 2008]. In this study this correction is not applied however. On the one hand, the application of the correction is not straightforward, since the IRGA used in this study is installed at an angle (~15% to 20%), while *Burba et al.* [2008] used a vertical configuration. On the other hand, this study focuses on the growing season, when temperatures rarely drop below zero and snow cover is absent. Under these circumstances, the influence of the surface heat exchange of the instrument on the cumulative fluxes would be limited and unlikely to have a large effect on flux measurements.

[12] To check for another possible measurement problem in the form of storage effects, the vertical stratification of CO_2 during nights with stable atmospheric conditions was measured with a vertical CO_2 profile [*de Araújo et al.*, 2008], which measured CO_2 concentrations at 5 heights. These 5 heights were installed along a nonlinear spacing from 15 cm above the ground to the measurement height of 4.7 m. Measurements of CO_2 concentrations were performed in the summer of 2008 and 2009 in varying conditions. Even under very stable nighttime conditions with high increases of CO_2 concentrations, no significant vertical concentration gradient was found. It is therefore unlikely that storage effects pose a problem at this site.

[13] In a second tower, additional measurements were performed of incoming and outgoing shortwave radiation (Kipp & Zn, Delft, Netherlands, type albedometer, CM7b), up-and-down-facing longwave radiometers (The Eppley Laboratory, Newport, Rhode Island, USA, type PIR) and a net radiometer (Campbell Scientific, Logan, Utah, USA, type Q7). Soil heat flux was measured with the use of soil heat flux plates (Middleton, Melbourne, Australia). Soil temperature was recorded from two locations at 10 depths along a 60 cm profile with soil temperature sensors (manufactured at the VU University Amsterdam, type Pb107). One of these profiles was placed in a dry and slightly higher situated area with shrubs, while the second profile was installed in an inundated depression dominated by sedges. Furthermore, an air pressure sensor (manufactured at the VU University Amsterdam) recorded barometric air pressure and precipitation that was measured with a tipping-bucket rain gauge (Campbell Scientific, Logan, Utah, USA).

2.3. Flux Partitioning

[14] The dynamics of net ecosystem exchange (NEE) are governed by two processes: GPP and R_{eco}. These components need to be extracted from the eddy covariance signal, which only measures NEE. The standard procedure is to determine the flux of ecosystem respiration (R_{eco}) first and then extract gross primary production (GPP) from the remaining signal, following the equation GPP = NEE − R_{eco}. This was previously done by *Reichstein et al.* [2005], who used the respiration model established by *Lloyd and Taylor* [1994] to estimate relationships between R_{eco} and air temperature from nighttime measurements of NEE. During Arctic summers however, it is problematic to derive R_{eco} from nighttime data since nights are very short. This problem can be alleviated by using the model presented by *Lasslop et al.* [2010], who combined the same respiration model with a hyperbolic light-response curve [*Falge et al.*, 2001], to use daytime data to estimate both R_{eco} and GPP as described in equation (1).

$$\mathrm{NEE} = -\frac{\alpha\beta R_g}{\alpha R_g + \beta} + R_{ref}\ \exp\left(E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T_{air}-T_0}\right)\right) \tag{1}$$

The left-hand side of this equation describes the light-response curve and represents GPP (which is negative by definition). Here, α is the canopy light utilization efficiency in mol C J^{-1} and describes the initial slope of the light-response curve. β is the maximum CO_2 uptake rate of the canopy at light saturation in mol C m^{-2} s^{-1}, and R_g is the incoming shortwave radiation in W m^{-2}. The right-hand term describes R_{eco} and follows the model established by *Lloyd and Taylor* [1994]. Here, R_{ref} is the reference respiration in mol CO_2 m^{-2} s^{-1} at the base temperature T_{ref} (set to

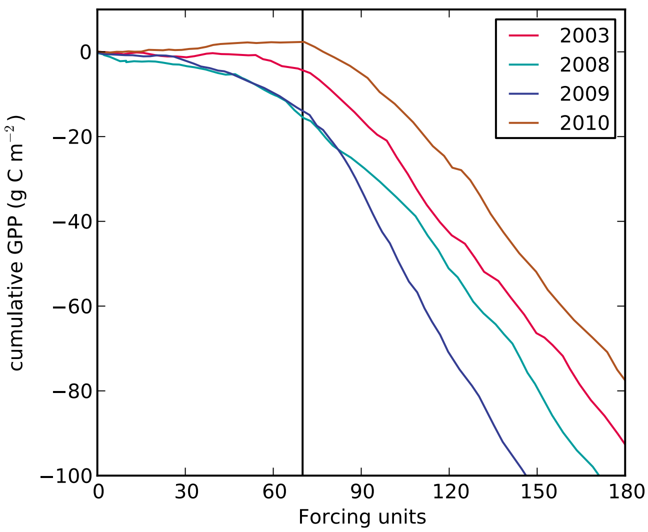

Figure 2. Relationship of cumulative GPP along the cumulative of forcing units (FU) for the complete years. At a value of 70 ($FU_{critical}$), bud break of *Betula nana* and *Salix pulchra* occurs, and this is defined as the start of the growing season. This moment is indicated by the vertical black line.

15°C), E_0 is the temperature sensitivity, T_{air} is the air temperature in C and T_0 is a constant parameter set at −46.02°C.

[15] Furthermore, *Lasslop et al.* [2010] adjusted the light-response curve in equation (1) to account for changes in VPD. By adding a relationship with VPD, the model correctly attributes a drop in NEE to a decrease in GPP instead of an increase in R_{eco} in summer afternoons with a high VPD. This effect of VPD on GPP was incorporated by adjusting the value of β for periods where VPD reached values higher than 10 hPa according to equation (2).

$$\beta = \begin{cases} \beta_0 \exp(-k(\mathrm{VPD} - \mathrm{VPD}_0)) & (\mathrm{VPD} > \mathrm{VPD}_0) \\ \beta = \beta_0 & (\mathrm{VPD} \leq \mathrm{VPD}_0) \end{cases} \qquad (2)$$

Here, k is a dimensionless parameter that tunes the decay with VPD. VPD_0 is the threshold of 10 hPa and β_0 is the original value of β before the VPD adjustment.

[16] To use this set of equations to achieve a good estimate for GPP and R_{eco}, first a moving window of 12 days over the nighttime data was applied to obtain the value of E_0, using the right-hand side of equation (1). This value for E_0 was then fixed and thereafter the daytime data was used to estimate R_{ref}, α and β every two days, with the full equation, on a window of 4 days. The procedure described here mostly follows *Lasslop et al.* [2010], however in this study the radiation limit to separate between daytime and nighttime was set to 20 W m^{-2} instead of 4 W m^{-2}. This is the same limit as used in the flux partitioning method by *Reichstein et al.* [2005] and this was done to make sure that in the period of the year close to summer solstice, enough nighttime data points were available to obtain an estimate of E_0. Otherwise, due to the short nights in this period of the year, the availability of data was significantly reduced and no optimization could be achieved for E_0. Using the daytime data to estimate R_{ref}, α and β however, provided enough data points to provide an overall reliable partitioning method.

2.4. Growing Season Length

[17] In the years 2003, 2008, 2009 and 2010, eddy covariance measurements were started several weeks before snowmelt, and fluxes were measured until after the end of the growing season (from now on referred to as "complete years"). Although measurements are lacking from springtime in the years 2004 to 2007 due to power failures combined with the inaccessibility of the site in that period (referred to as "incomplete years"), most of these years (2004 to 2006) were started within days from bud break, which occurs around 4 weeks after snowmelt. This period before bud break usually shows some respiration and GPP (i.e. from grasses and sedges) which both total to approximately 10 g C m^{-2}. However, these amounts are very small compared to fluxes during the growing season when these amounts of carbon can be exchanged within 2 or 3 days, instead of 4 weeks. Therefore, although these springtime fluxes are missing in 4 measurement years, comparisons that are limited to the growing season will still capture most of the interannual variability.

[18] To compare these growing seasons with each other, cumulative fluxes of NEE, GPP and R_{eco} need to be established. However, to be able to make these estimates, the length of the growing season has to be defined. Since the exact start of the growing season is unknown for the incomplete years, the complete years were studied for relationships that could predict bud break for each year, preferably with temperature. Continuous temperature measurements of this region are available for all years from the weather station of the nearby town of Chokurdakh (about 30 km). These temperature readings and the onset of snowmelt at this weather station were highly comparable to the study site and could therefore be used to predict the start of the growing season of the incomplete years.

[19] The required relationship between temperature and bud break was previously found by *Pop et al.* [2000]. In their work, it was shown that a certain buildup of temperature, expressed as forcing units (FU), was needed for the shrubs *Betula nana* and *Salix pulchra* to achieve bud break. Since these shrubs are the dominant shrub species in the study area of this research, we could use the same relationship, as shown in equation (3), to predict bud break at our site.

$$\mathrm{FU\ day}^{-1} = \begin{cases} 0 & (T_{air} \leq 0°\mathrm{C}) \\ 10/(1 + \exp[0.08(T_{air} - 18.0)]) & (T_{air} > 0°\mathrm{C}) \end{cases} \qquad (3)$$

Here T_{air} is the air temperature in °C. The outcome of this equation was used to calculate the cumulative amount of these forcing units since snowmelt. These values were plotted against the cumulative amount of GPP as shown in Figure 2. From this figure it is clear that GPP picks up much more strongly when the cumulative forcing units hit a value of 70 FU, also known as $FU_{critical}$. This relationship with FU was then applied to the incomplete years to estimate the start of the growing season (GS_{start}).

[20] While the start of the growing season showed a high variability among years, due to differences in spring tem-

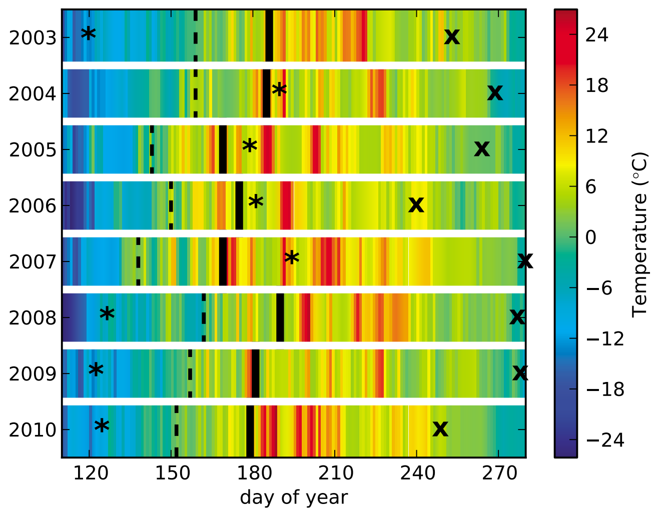

Figure 3. Interannual differences in the starting day of snowmelt (SM, indicated by the dashed line), the starting day of the growing season (GS_{start}, indicated by the thick line), the starting day of the eddy covariance (EC_{start}, indicated by the asterisk) and the ending day of the eddy covariance (EC_{end}, indicated by the cross). The colors indicate the temperature observed in these years (in degrees Celsius).

peratures, each year GPP ceased in early September. Around this time, daylight quickly diminishes and temperatures start to drop. This is confirmed by the eddy covariance data, where the NEE switches from a net uptake to a net emission of carbon at the end of August. Since this happens in a very predictable way each year and closely around the same date, it was chosen to define the end of the growing season a few days after this switch at September 7 (DOY = 250). The difference between this date and GS_{start} provided the length of the growing season.

2.5. Uncertainty Assessment

[21] After the relationship with cumulative forcing units was applied to establish bud break, and with it the start of the growing season, it was observed that for the incomplete years the start of the growing season was missed by a few days due to power failures. To simulate the cumulative amounts of R_{eco} and GPP for these periods, the daily averages of the complete years were examined to establish relationships that could be used to model the cumulative fluxes. In the case of R_{eco}, estimates of E_0 and R_{ref} were obtained by averaging these parameters for all years. This averaging was not done along the day of year (DOY) because snowmelt does not occur at the same day each year, which leads to large interannual differences along day of year. Instead, to obtain a more realistic average of R_{ref} and E_0 in relation to snowmelt, these parameters were averaged along the number of days since snowmelt (DSM). The air temperature from the weather station in Chokurdakh, together with the average of the R_{eco} parameters, could then be used to estimate R_{eco} for the incomplete years. These estimates were also extended into the period between snowmelt and bud break, to obtain an estimate of R_{eco} during this period.

[22] The amount of GPP in the pre-growing season period was estimated from Figure 2. As can be seen here, the fluxes before bud break show a similar pattern with FU and average values of GPP with FU were used to estimate GPP in this period. Thereafter, to calculate the missing GPP within the growing season, an average of the parameters from equation (1) could not be used, since no measurements for radiation were available from the local weather station. As an alternative, the cumulative flux was estimated from the average of the GPP flux from July. Although a rough estimate, average GPP rates are rather stable at this site when compared to long time periods.

[23] Since both these estimations have their limitations, it had to be assessed what their uncertainty range was. Therefore, the same cumulative flux estimation was used on the complete years but for periods with the same length as in each incomplete year. The highest departure from the measurements due to these artificial data outages, was used as the uncertainty range of the estimate for the incomplete year that corresponded to that particular data outage. By defining the uncertainty range in this way, the range represents a likely maximum uncertainty.

[24] Apart from the uncertainty that is caused by the system being inoperative however, the random error inherent to the measurements and the gap-filling of small gaps in the data, due to data filtering and small power outages, both contribute to extra uncertainty [*Goulden et al.*, 1996; *Dragoni et al.*, 2007] and should be determined. The standard deviation of the random measurement error in the half-hourly observations, $\sigma(\epsilon_F)$, was calculated according to *Hollinger and Richardson* [2005] with the use of the successive days approach. The uncertainty due to the gap-filling method used, ϵ_G, was assessed by transposing the gap distribution of one year to all the other years and repeating the gap-filling technique on these artificial gaps. The standard deviation of the difference between the observed data and the filled artificial gaps was used to represent $\sigma(\epsilon_G)$. After determining these standard deviations of random measurement uncertainty and the gap-filling technique, they were used in a Monte Carlo simulation to assess the uncertainty in the seasonal totals according to *Dragoni et al.* [2007]. A random error, ϵ_S, with a double exponential distribution and zero mean was applied to each NEE value, where the standard deviation of ϵ_S was equal to $\sigma(\epsilon_F)$ for the half-hourly values that were directly measured and equal to $\sigma(\epsilon_G)$ for those values that were gap-filled. By applying this artificial random error, a simulated NEE could be calculated according to $NEE_S = NEE + \epsilon_S$, of which the sum represents the simulated cumulative flux over the period of interest. This procedure was repeated 10000 times, whereafter the standard deviation of all 10000 runs was used to represent the uncertainty in the flux due to random measurement error and gap-filling.

3. Results

3.1. Environmental Conditions

[25] In Figure 3, we indicate the starting day of the eddy covariance measurements (EC_{start}), the ending day of the eddy covariance measurements (EC_{end}), snowmelt (SM), the starting day of the growing season (GS_{start}) and the average daily temperatures for the measured years. Here it can be

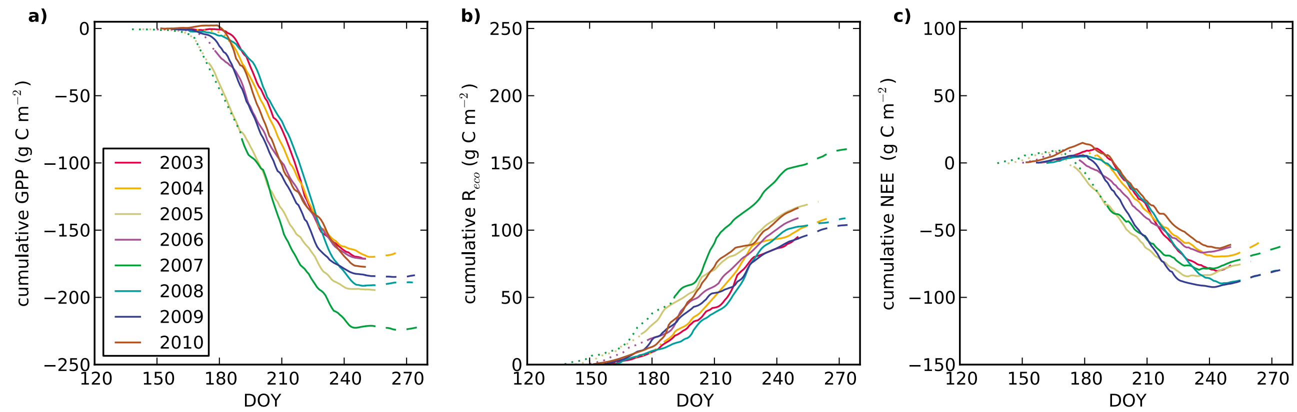

Figure 4. Cumulative fluxes of (a) GPP, (b) R_{eco} and (c) NEE from snowmelt onward plotted against the day of year. The incomplete years where early fluxes have been simulated are plotted with a dotted line. The data measured after the end of the growing season (DOY = 250) is plotted with a dashed line.

seen that the eddy covariance setup failed to measure the springtime fluxes from 2004 to 2007, due to power failures. The subsequent data loss led to 1, 6, 3 and 22 missing days at the start of the growing seasons of 2004 to 2007, respectively. In those years, the measurements could not be started again until after snowmelt, since the site is inaccessible during that period. However, apart from 2007, in most years the measurements were started soon after the start of the growing season (1 to 6 days) and most of the carbon exchange was measured.

[26] Furthermore, Figure 3 shows a wide range in the timing of snowmelt. 2005 and 2007 saw a very early snowmelt, already on May 25 and May 18, respectively. Historical data from the weather station in the nearby town of Chokurdakh confirms that these snowmelt dates are earlier than normal. In other years, snowmelt at the study site occurred between May 30 and June 10, which is more typical when compared to long term data from the local weather station. Snowmelt was furthermore closely linked to the start of the growing season, which usually followed within 4 weeks (±4 days). The years with earlier snowmelt therefore also had an earlier start of the growing season.

[27] These changes in snowmelt and start of the growing season are also reflected in the temperatures in Figure 3. Obviously, years with earlier snowmelt show higher temperatures earlier in the year. Notably, the highest average temperature for any year was also observed for the year with the earliest snowmelt, 2007. The year with the highest monthly average however is 2010, when the average July temperature reached 15°C. During that month, record temperatures above 30°C were measured at the site and at the Chokurdakh weather station. On the other hand, the preceding year showed the lowest average temperatures for July and August and this stresses the high interannual variability in weather at this site.

[28] Opposed to these large interannual differences in the spring and summer, autumn temperatures are much more comparable among years. In the weeks following DOY = 250, temperatures are low, mostly <5°C and sometimes below freezing, and show little variation among years due to the shorter and darker days in this period.

3.2. Fluxes

[29] The large differences in the onset of snowmelt and summer temperatures among years are reflected in GPP, R_{eco} and NEE. In Figure 4, the cumulative totals of GPP, R_{eco} and NEE are plotted against the day of year, starting at the day of snowmelt. The estimates of springtime fluxes for the incomplete years have also been plotted (the dotted lines in the figure), to show how these estimates fit alongside the fluxes measured in other years. From these cumulative plots, an estimate of the total fluxes of each growing season are given in Table 1.

[30] Figure 4 and Table 1 show that growing season GPP and R_{eco} are quite variable. GPP varied between −158 to −184 g C m^{-2}, while R_{eco} varied between 74 and 104 g C m^{-2}. These ranges are without the estimate for 2007, which showed exceptionally high GPP and R_{eco} rates (−211 and 129 g C m^{-2}, respectively). Surprisingly, the estimate of NEE for 2007 (−82 ± 29 g C m^{-2}) was very typical. NEE of all years varied between −69 and −95 g C m^{-2}.

[31] These numbers are not without their uncertainties however, as shown in Table 1. In the incomplete years, power failures caused complete data loss in the beginning of the season. By simulating fluxes for these periods with relationships derived from the other years (complete years) and the average GPP rate during the growing season, estimates of the cumulative sums of the missing periods could be made. The uncertainty range due to the missing periods in 2004 to 2007 varied between ±2–28 g C m^{-2} for GPP and ±2–8 g C m^{-2} for R_{eco}. Expressed in percentages, these ranges equate to ±1%–13% for GPP and ±2%–6% for R_{eco}. In NEE these ranges equate to ±5%–16% for the years 2004 to 2006 and ±35% for 2007. The uncertainty in NEE is somewhat higher here due to the fact that for these early season data outages, NEE was not directly simulated but rather derived as the sum of the simulated R_{eco} and GPP, which increases the error.

[32] Besides these uncertainties from the early season power outages in the incomplete years, the random measurement error and the error due to the common Fluxnet procedure for gap-filling short gaps [*Reichstein et al.*, 2005; *Moffat et al.*, 2007] were determined for both the incomplete and the complete years and were added to the uncertainty

Table 1. Estimates of Total GPP, R_{eco} and NEE During the Growing Season (gs) and During the Snow-Free (sf) Period for the Measured Years[a]

Year	GPP_{gs}	$R_{eco,gs}$	NEE_{gs}	GPP_{sf}	$R_{eco,sf}$	NEE_{sf}
2003	−166 ± 2	79 ± 2	−87 ± 2	−171 ± 2	95 ± 2	−77 ± 2
2004	−158 ± 4	84 ± 2	−74 ± 4	−168 ± 12	99 ± 5	−69 ± 13
2005	−184 ± 13	101 ± 5	−83 ± 13	−194 ± 18	117 ± 8	−77 ± 19
2006	−161 ± 7	92 ± 2	−69 ± 7	−171 ± 16	108 ± 6	−63 ± 17
2007	−211 ± 28	129 ± 8	−82 ± 29	−221 ± 30	147 ± 11	−74 ± 32
2008	−176 ± 1	87 ± 1	−89 ± 1	−191 ± 2	102 ± 2	−89 ± 2
2009	−168 ± 1	74 ± 1	−95 ± 1	−183 ± 1	93 ± 1	−90 ± 1
2010	−180 ± 1	104 ± 1	−76 ± 1	−177 ± 1	116 ± 1	−61 ± 1

[a]All totals are in g C m^{-2}. For the complete years (2003, 2008–2010) standard deviations indicate measurement and gap-filling uncertainty, while for the incomplete years (2004–2007) this also includes the uncertainty due to the simulated fluxes for the missing periods in the early season.

estimate. Among years, these were found to be rather similar, in the range of 1 to 2 g CO_2 m^{-2} or ~2% of NEE.

[33] The totals of GPP, R_{eco} and NEE, and the uncertainties mentioned above, are plotted in Figure 5 against the length of the growing season (GS_{length}) and the growing season temperature sum (ΣT_{gs}). For each of these plots, a weighted least squares regression was performed to assess whether any significant patterns occurred. Those regressions where the slope was significantly different from zero ($p < 0.05$) are shown here. From this it becomes obvious that GPP and R_{eco} show a significant relationship with ΣT_{gs} while the relationship with GS_{length} is less clear. Most importantly, while GPP and R_{eco} vary significantly with changes in ΣT_{gs} and show some variation along GS_{length}, there is no large variation in NEE. Apparently the increase in R_{eco} is mostly offset by an increase in GPP due to the longer growing season. However, the slope of NEE vs ΣT_{gs} shows a trend (slope = 0.041) toward less uptake with warmer summers, which is nearing significance ($p = 0.13$). Furthermore, the highest NEE occurred in 2008 and 2009, years which showed the shortest growing season and the coldest summer, respectively. This suggests that R_{eco} increases more than GPP with warmer and longer growing seasons.

4. Discussion

4.1. Uncertainty Assessment

[34] As shown in Table 1, the cumulative fluxes for the complete years (2003, 2008, 2009 and 2010) could be well determined, including uncertainties in the totals due to random measurement error and the gap-filling procedure used. For the incomplete years however (2004 to 2007), the start of the growing season was missed due to power failures. In 2004 to 2007, the start of the growing season was missing 1, 6, 3 and 22 days, respectively. After simulating the fluxes of GPP and R_{eco} for these periods, estimates of the cumulative flux for the incomplete years could be made as well. The addition of this simulated flux led to a large uncertainty in the total GPP of 2007 due to the large period of data loss and the associated uncertainty is therefore much larger. This particularly large period without measurements occurred because the growing season started exceptionally early and the measurements were restarted later than usual. However, although this range in GPP is large, it is likely that the estimate of total GPP is somewhat overestimated during that season. The GPP was simulated by extrapolating the average GPP from the month of July, a period that showed exceptionally high GPP rates, to the missing 22 days. By simulating the start of the growing season with these high rates, it is likely that the estimate of GPP for 2007 is somewhat too high and unlikely to be even higher. Therefore, if we do not see an increase in NEE, even with these (possibly) overestimated GPP totals, it is likely that an earlier onset of the growing season will not lead to more uptake of carbon.

[35] The simulated R_{eco} in the same missing periods, was obtained through temperature measurements from the weather station in Chokurdakh together with the respiration model by *Lloyd and Taylor* [1994]. The parameters R_{ref} and E_0 of this equation were estimated by using averages from other years. This method led to much smaller uncertainty ranges than for the estimation of GPP since temperature differences of that year were incorporated. The estimate for 2007, due to the late start of the measurements in that year, is again more uncertain but the range is much smaller for the estimate of R_{eco} than for GPP.

[36] Besides the uncertainty caused by the missing periods at the beginning of the incomplete years, the uncertainty due to random error in the measurements and due to the gap-filling method used, was also determined. This led to an uncertainty of about 2% in the NEE over the growing season. This percentage seems low, since previous research has reported values from 3% to 5% in annual NEE estimates [*Goulden et al.*, 1996; *Dragoni et al.*, 2007]. However, those estimates were obtained in forests, where below canopy effects, such as storage, can have significant effect on measurement errors. To investigate whether storage effects were present in the short tundra vegetation of this study, measurements were performed with a vertical CO_2 profile. These measurements showed no appreciable vertical stratification in CO_2 concentrations during stable nocturnal conditions. This means that a systematic error due to storage effects is likely to be small or absent and this reduces the error inherent in the measurements. Furthermore, measurements in this study were performed over a much shorter period (60 to 81 days), while previous studies investigated yearly totals, which is likely to lead to different uncertainties also. A further explanation might be that absolute fluxes are relatively low at this site when compared to forests and it is well known that errors in flux measurements scale with the flux magnitude [*Richardson et al.*, 2006], increasing confidence in these low uncertainties.

4.2. Growing Season Length

[37] Apart from the added uncertainty from measurement errors and data gaps, possibly an additional error is introduced by comparing the totals of GPP, R_{eco} and NEE over the full growing season instead of exactly the same window for each year. The difference in growing season length shows a spread of three weeks and fluxes that are measured before the start of the growing season are not accounted for. Unfortunately, the amount of GPP of the period before the start of the growing season was unknown for the incomplete years. An estimate for these years can be made from the available data in the complete years. This estimate showed that GPP was near zero before snowmelt, as expected. After

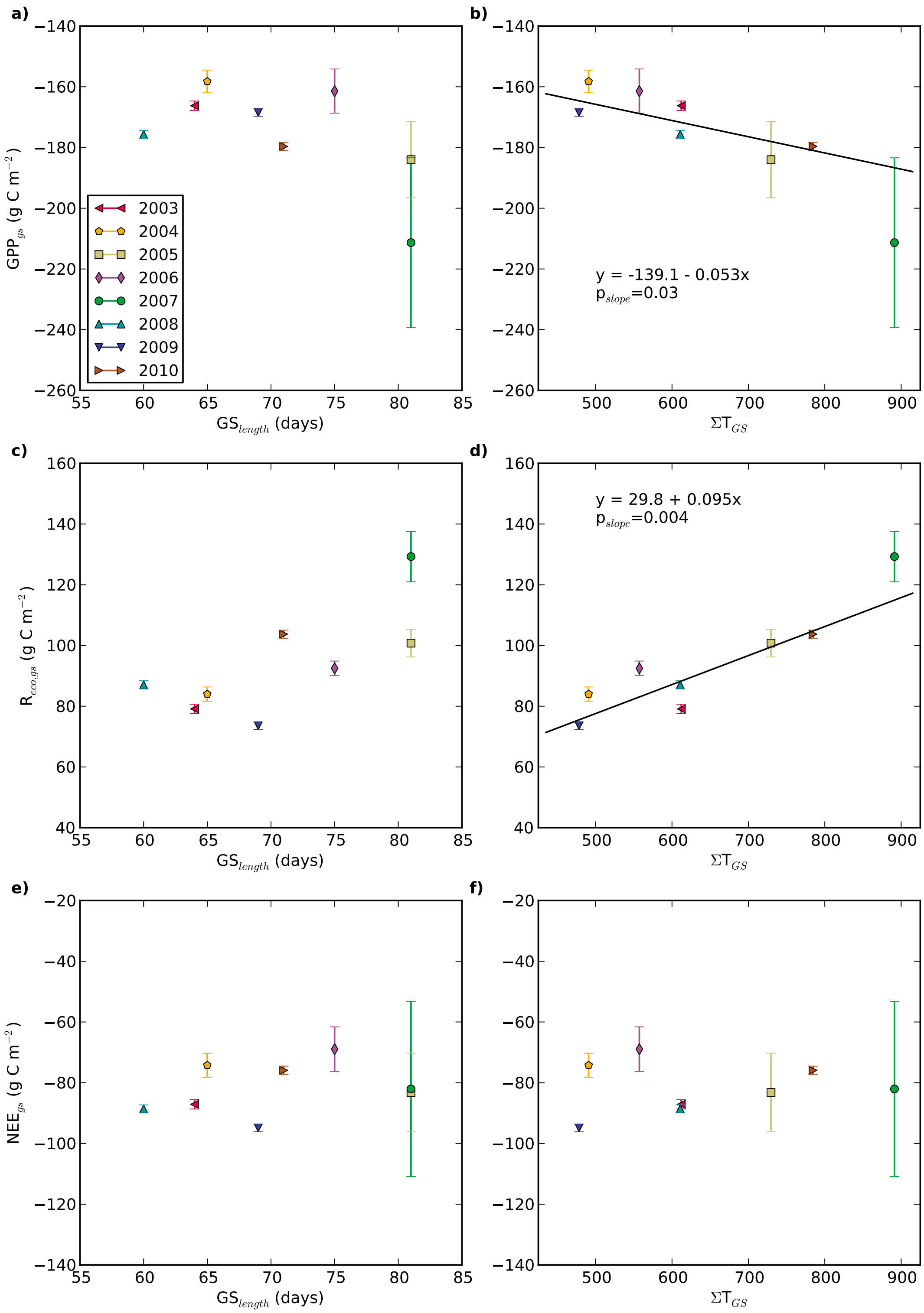

Figure 5. Total fluxes of (a, b) GPP, (c, d) R_{eco} and (e, f) NEE plotted against the day of snowmelt and the average temperature during the snow-free period. For the complete years (2004, 2008–2010), the error bars denote measurement and gap-filling uncertainty, while for the incomplete years (2004–2007), this also includes the uncertainty due to the simulated flux of the early growing season periods when measurements were lacking. For those plots where the slope of the weighted least squares regression was significant ($p < 0.05$), the regression has been plotted.

snowmelt it picked up slowly until the start of the growing season. At that date, the cumulative amount of GPP ranged from close to zero to 16 g C m^{-2} as shown in Figure 2. Similar values were found for R_{eco}. The cumulative exchange of carbon before snowmelt was in the order of 1 to 2 g C m^{-2}. After snowmelt, total R_{eco} amounted to 12 to 20 g C m^{-2}.

[38] Since the cumulative amounts of GPP and R_{eco} in between snowmelt and the start of the growing season are of similar size, the cumulative sum of NEE was not much affected since they largely cancel each other out, with R_{eco} being slightly larger. By incorporating measured or estimated springtime fluxes, the patterns from Figure 5 were not significantly altered. Nonetheless, to provide a complete picture, the fluxes of GPP, R_{eco} and NEE from snowmelt until the end of the growing season have also been included in Table 1. Fluxes before snowmelt were omitted, since they were found to be close to zero.

[39] While the variable start of the growing season had a limited effect on NEE, the selection criterion for establishing the end of the growing season possibly introduces another error since fluxes after the end of the growing season are also ignored. However, as can clearly be seen from Figure 4, the cumulative amount of carbon fluxes of those years where autumn fluxes were measured, showed very similar slopes after the end of the growing season. Although autumn fluxes were not measured every year, due to power failures, it can be seen that the interannual difference in the slopes of GPP, R_{eco} and NEE is low. GPP is near zero in this period and therefore interannual differences in NEE should be mostly due to differences in R_{eco}. Respiration is however very similar among years due to highly comparable autumn temperatures as shown in Figure 3. Even for the year 2007, which had the highest temperatures for September, the pattern is not very different. We therefore conclude that fluxes measured from the end of the growing season until the start of snowmelt in the following year, show much more similar patterns among years and are not expected to introduce large changes in the relative differences in carbon fluxes among years.

4.3. Relationship With Growing Season Length and Summer Temperatures

[40] With the uncertainties constrained, we are confident that the relative interannual differences will be governed mostly by variations in GPP and R_{eco} during the growing season. Therefore, total amounts of growing season GPP, R_{eco} and NEE were plotted in Figure 5 against growing season length (GS_{length}) and the growing season temperature sum (ΣT_{gs}).

[41] With the exception of the (possibly too high) estimate of 2007, it appears that the total amount of GPP does not vary greatly with length of the growing season and no significant slope could be found. On the other hand, GPP does show a significant increase with the growing season temperature sum, as shown in Figure 5b. It seems that in this ecosystem a higher sum of temperatures leads to more GPP but that a longer growing season does not necessarily lead to more uptake of carbon.

[42] The relationship between growing season length and R_{eco} in Figure 5c, seems to show a clear positive relationship with growing season length. This seems logical: a longer growing season leads to a longer period where respiration can take place and the total amount of respiration will increase. However, the slope of the weighted least squares regression through these data points was not significantly different from zero (p = 0.16). On the other hand, R_{eco} did show a significant regression with ΣT_{gs} as shown in Figure 5d. This is not surprising, since respiration has been simulated with the use of the respiration model of *Lloyd and Taylor* [1994], which is highly dependent on temperature. However, it has been shown that this model can correctly approximate respiration on tundra [*Lund et al.*, 2010] and previous research at the study site, has shown that a similar Q10 relationship with temperature agreed well with flux chamber measurements measured at the same site [*van der Molen et al.*, 2007].

[43] Since both GPP and R_{eco} increase with higher summer temperatures, NEE depends on which of the two fluxes increases more. Figure 5 clearly shows no relationship between NEE and either growing season length or the sum of temperatures and no significant regression could be found. If anything, the figure shows that it is unlikely that the uptake of carbon in this ecosystem is increased by a longer and warmer growing season. Years where the growing season was short or the summer temperature sums were low, showed the highest uptake of carbon, while the years where the growing season was long or warm showed the least uptake of carbon, with the exception of 2004. Furthermore, the slope of the regression of NEE with ΣT_{gs} was nearing the significance level for a slightly diminished uptake with warmer growing seasons (slope = 0.041, p = 0.13).

[44] Arguably equally important is the observation that, even if the net carbon uptake were to stay stable with higher summer temperatures, the longer growing season will lead to higher methane fluxes [*van der Molen et al.*, 2007; *Parmentier et al.*, 2011]. And while methane fluxes from the study site are very variable among years because of different water availability and temperatures, a longer snow-free period leads to more time in which more methane fluxes can be emitted to the atmosphere. Importantly, a longer and warmer growing season does not necessarily lead to dryer conditions, since it was observed in the field that 2007 was very wet compared to other years and high methane fluxes were measured [*Parmentier et al.*, 2011]. These emissions of methane cannot possibly be offset by an increase in carbon uptake and therefore the strength of the greenhouse gas sink of this ecosystem is likely to diminish in a warmer climate.

[45] These results are different from previous studies on the influence of the growing season to NEE. For example, *Aurela et al.* [2004] showed that for a subarctic fen without permafrost, cumulative NEE was completely determined by the timing of snowmelt, contrary to what was found in this study. The results from *Aurela et al.* [2004] were confirmed by *Lafleur and Humphreys* [2007], who also found a clear relationship with growing season length for a Canadian tundra site. Furthermore, *Groendahl et al.* [2007] showed that for a High Arctic site in Greenland, NEE clearly increased with warmer summers although it has previously been suggested that NEE in the High Arctic is more likely to increase with higher temperatures than at lower latitudes [*Welker et al.*, 2004]. In previous research on the carbon balance of this site [*van der Molen et al.*, 2007], it was

shown that this site exhibits a rather large uptake of carbon when compared to other tundra sites around the Arctic. This was postulated to be due to the continental climate which facilitates warm summers, stimulating GPP, while the soil temperature lags the air temperature, limiting respiration. When comparisons are made to other sites, the different climatic factors should therefore be taken into account and this might explain differences with studies that did show an increase with longer growing season or warmer summers. Different sites obviously show different responses in R_{eco} and GPP with higher temperatures and longer growing seasons, and the covariance of the two carbon fluxes will therefore determine the future fate of the carbon sink of these sites.

5. Conclusion

[46] In this study, the net ecosystem exchange of a graminoid tundra site, measured over 8 consecutive years, has been split up into its components, gross primary production and ecosystem respiration. The component fluxes were subsequently compared to the climatic differences among years, with an emphasis on growing season length and the growing season temperature sum. While the length of the growing season showed an unclear relationship with GPP, an increase in GPP was shown to be associated with a higher growing season temperature sum. However, at the same time, warmer growing seasons also led to more respiration.

[47] The net carbon exchange that resulted from these two opposing fluxes showed no relationship to the studied climate variables. However, it was found that the years with the highest net uptake of carbon had the shortest growing season or the lowest temperatures. On the other hand, the years that showed the least amount of net carbon uptake mostly had long growing seasons or high summer temperatures. This leads us to conclude that the amount of carbon that is taken up by this ecosystem is more likely to decrease than to increase with longer growing seasons and higher summer temperatures.

[48] This conclusion contrasts with those of previous studies in which the net uptake of carbon was shown to be enhanced by longer or warmer growing seasons. Our contradictory results probably stem from site-specific differences, such as soil and climate type, which cause the responses of respiration and GPP to climatic changes to be different in magnitude. We therefore conclude that net carbon uptake around the Arctic will show nonuniform changes to longer and warmer growing seasons.

[49] **Acknowledgments.** We wish to acknowledge the people at the Institute for Biological Problems of the Cryolithozone, Siberian Branch of the Russian Academy of Science, in Yakutsk for their assistance in and outside the field, without whom it would have been impossible to establish this long data set. Also, we wish to thank T. G. Strukova and the rangers of the Kytalyk Resource Reservation for their logistical support to and from the site and other assistance. Furthermore, we wish to thank the engineering and electronics workshop at the VU University Amsterdam, without whom the successful installation, maintenance and operation of the equipment would not have been possible. Finally, we wish to acknowledge the Darwin Center for Biogeosciences, which supported this research with a grant to F. J. W. Parmentier (142.16.1041), and COordination action Carbon Observing Systems (COCOS) of the seventh framework program (grant 212196), which provided additional funding to enable this research.

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